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## Thermal responses for men with different fat compositions during immersion in cold water at two depths: prediction versus observation

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**Abstract** A cold thermoregulatory model (CTM) was applied to data from partially immersed subjects divided into normal (NF) or low fat (LF) groups in order to validate CTM during immersion at two depths and to examine mechanisms underlying the individual differences. CTM defines thermal characteristics, e.g. surface area and maximal shivering intensity, using height, weight, fat %, age and  $VO_{2max}$ . Ten clothed subjects, 5 NF (15–19%) and 5 LF (8.1–14.7%), were immersed in both 10 and 15°C water at chest (CH) and waist (WA) level. Environmental and clothing inputs for CTM were weighted to adjust for the ratio of skin surface area covered by either air or water at various immersion depths. Predicted core temperature ( $T_c$ ) responses for each individual trial were compared with measured data. There were no significant differences ( $P > 0.05$ ) between measured  $T_c$  and predicted  $T_c$  for NF at all four conditions. In contrast, for the LF group, the predicted  $T_c$  responses were all higher than measured ( $P < 0.05$ ). However, predicted  $T_c$  agreed closer with measured  $T_c$  for LF when leg muscle blood flow was increased in the simulation. This suggests that blood flow may contribute to the rapid decline in  $T_c$

observed in LF and its variance may cause in part the individual differences in  $T_c$  responses. CTM predicts  $T_c$  responses to immersion at various depths with acceptable accuracy for NF individuals in this study and can be adapted to non-uniform environments.

**Keywords** Model · Cold stress · Hypothermia · Thermoregulation · Muscle blood flow

### Introduction

One of the difficulties in establishing criteria for cold survival or injury prevention and in developing cold thermoregulatory models is the intra- and inter-individual differences in the cold response. For example, in Molnar's survival time curve, survival times ranged from 2 to 50 h during immersion in ocean water of 20–24°C (Molnar 1946). There is no simple explanation as to why such large inter-individual differences exist and what the parameters are in determining individual responses. Potential factors include height, weight, body fat, shivering capacity, blood flow and immersion depth, etc. These factors impact either physiological (shivering, vasoconstriction, vasodilation) or biophysical (heat transfer from the core to the body surface through conduction and blood flow convection) processes of heat balance.

Body fat is a significant factor in the relationship between human thermal equilibrium and environmental cold stress (Toner and McArdle 1996; Stocks et al. 2004). The fat influences the physiological and internal thermal processes in two ways: (1) it provides insulation since its conductivity is low (Werner and Buse 1988; Toner and McArdle 1988); and (2) it is typically

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associated with low metabolism and thus attenuates shivering heat production (Tikuisis et al. 1988). Most studies report an inverse relation between body fat composition and  $T_{\text{c}}$  cooling rate (Hayward and Keatinge 1981; Veicsteinas et al. 1982; McArdle et al. 1984) although one study showed that subjects with low fat maintained a similar core temperature ( $T_{\text{c}}$ ), compared to their high fat counterparts, due to a significantly greater shivering thermogenesis during immersion in 18, 22 or 26°C water (Glickman-Weiss et al. 1991). Since body fat plays an important role during cold exposure, it is necessary for thermoregulatory models to take this factor into account in order to differentiate  $T_{\text{c}}$  responses in populations with various body fat compositions. Within population, body fat composition can be changed significantly after intensive training (Friedl et al. 1994) and consequently the capability in defending cold may change too.

Muscle blood flow is another factor which influences heat balance and internal heat transfer process. However, quantitative information on relationships between muscle blood flow and human thermal responses to cold is limited, because muscle blood flow is difficult to measure accurately. A recent study measured muscle blood flow using an optic fiber and demonstrated the potential contribution of muscle blood flow to changes in  $T_{\text{c}}$  after exercise in 25°C air (Kenny et al. 2006). The contribution of muscle blood flow would be expected to be greater during cold water immersion due to higher temperature gradients between the core and extremities. One optional approach to study the impact of muscle blood flow on heat balance and  $T_{\text{c}}$  responses could be through simulation using human thermoregulatory models.

Biophysical analysis of heat balance becomes more complicated during partial immersion since the external environment is not homogenous, i.e. people are simultaneously exposed to both air and water environments. Consequently, no cold model has validated its prediction capacity under partial immersion conditions. A study was conducted to examine the role of immersion level and water temperature on  $T_{\text{c}}$  during light exercise. The subjects were ten young healthy men with body fat compositions ranging from 8.1 to 19%. The present study applied our cold thermoregulatory model (CTM) (Xu et al. 2005) to analyze this physiological data. CTM uses five biophysical characteristics, including the percentage of body fat, to define the overall thermal characteristics/properties of each individual. The goals were (1) to determine whether CTM can predict thermal responses for each individual with various fat composition during immersion in cold water at two depths; and (2) to find out which factors

or mechanisms (i.e. fat %, shivering or muscle blood flow) may contribute to large individual differences, especially in individuals with low body fat composition. By modeling the effects of different immersion levels in combination with body composition, the potential life-threatening hazard of partial immersion may be better understood, and more active preventive measures can be implemented or public warnings issued.

## Methods

### Cold thermoregulatory model

Cold thermoregulatory model was derived from the previous version of a thermoregulatory model developed by Werner and Webb (1993), which was based on the essential developments of Stolwijk and Hardy (1977). It was a six-cylinder model, with each cylinder consisting of a core and shell layer. Recently, we added muscle, fat and clothing layers (Xu and Werner 1997) and incorporated a conceptual model for shivering intensity and fatigue into the current CTM configuration (Xu et al. 2005). This has improved its performance for predicting human responses to long-term cold exposure. Each cylinder is now divided into concentric compartments representing the core, muscle, fat, and skin. The outer cylinder has an additional clothing layer. Circulation is represented as a one-loop circulatory system and is an independent compartment. Thus, the human body is represented by 25 compartments. The sizes of the compartments are determined from height, weight and percentage of body fat (Xu 1996).

In the active system, an integrated thermal signal to the thermoregulatory controller is composed of the weighted thermal input from thermal receptors at various sites distributed throughout the body. The integrated body temperature is weighted using the core, muscle and skin compartment temperatures. The afferent signal is the difference between this temperature and its threshold, which activates thermoregulatory mechanisms including vasomotor changes, sweat production and metabolic heat production (Xu and Werner 1997). Shivering thermogenesis (i.e. part of metabolic heat production) is a function of core and mean skin temperatures, and includes an intensity adjustment, maximal capability, shivering exhaustion, and inhibition due to a low core temperature (Xu et al. 2005). The maximal shivering intensity was estimated from the height, weight,  $\text{VO}_{2\text{max}}$  and age (Eyolfson et al. 2001).

CTM inputs include individual characteristics (i.e. height, weight, percentage of body fat, age,  $\text{VO}_{2\text{max}}$ )

and exercise intensity, as well as environmental (i.e. temperature, humidity, and wind velocity) and clothing (clothing insulation  $i_{cl}$ , moisture permeability index  $i_m$ ) properties for each of the six cylinders.

### Experimental data

Ten male subjects volunteered for the experiment. Their physical characteristics are listed in Table 1. This study was approved by the appropriate Scientific and Human Use Review Boards of the U.S. Army Research Institute of Environmental Medicine and US Army Medical Research and Materiel Command. The subjects volunteered after being fully informed of the requirements and risks associated with the research. For analysis purpose, subjects were grouped according to their percentage of body fat as low body fat (LF  $\leq 14.7\%$ , five subjects A–E) or normal body fat (NF  $\geq 15.0\%$ , five subjects F–J). The percent body fat was determined from the equation of Durnin and Womersley using four skinfolds (Durnin and Womersley 1974). Subjects walked at  $0.44 \text{ m s}^{-1}$ , at two different immersion depths (waist to the iliac crest and chest to the nipple) and at two different water temperatures (10 and  $15^\circ\text{C}$ ). The air temperature near the head and chest ranged from 15 to  $22^\circ\text{C}$ , depending on the water temperature. Subjects put their arms on a plastic platform to keep their arms out of water. All trials were separated by at least one day of rest. Subjects wore the US Army battle-dress uniform (BDU; dry clothing insulation value of 1.3 clo), socks, and neoprene water shoes during exercise-cold water immersion. No caffeine or alcohol was consumed on the test day. Rectal temperature ( $T_{re}$ ) was measured using a rectal probe (YSI, Yellow Springs, OH, USA) inserted 10 cm beyond the anal sphincter. Skin temperature ( $^\circ\text{C}$ ) and heat flow ( $\text{W m}^{-2}$ ) were measured by heat flow sensors with an integrated thermistor (Concept Engineering, Old Saybrook, CT, USA) attached on the skin surface at eight sites (on the right side): anterior aspect of forearm, forehead, subscapular, triceps, pectoralis major, abdomen (7.5 cm lateral to umbilicus), anterior thigh, and calf. Temperature data were collected every 15 s during treadmill walking (PX 1006, National Instruments). Oxygen uptake ( $\text{VO}_2$ ) was determined using an online metabolic analysis system (Sensormedics Vmax, Yorba Linda, CA) before exercise and ~every 20 min during walking. Subject's expired air was collected for 5 min each time using a mouthpiece and noseclip. The order for the four trials/test conditions was randomized and counterbalanced. Each subject's trial began at approximately the same time each day. They walked on an underwater treadmill until one of the following

occurred: their rectal temperature reached  $35.5^\circ\text{C}$ , they had exercised for 4 h, the subject asked to stop, or subject's exposure was stopped by the principal investigator. Each combination was to be tested once, with seven of ten subjects completing four trials. Two subjects completed three trials and one subject completed only two trials, they stopped their participation and voluntarily withdrew from the study. Thus, the total number of trials completed was 36.

### CTM input adjustment for partial immersion

From a simulation viewpoint, the environments that subjects were exposed to were complex as conditions were not uniform, i.e. subjects were exposed to both air and water at the same time. The clothing was either wet or becoming wet from the absorption of water during the experiments. Of the six CTM cylinders, the head, arms and hands were always exposed to the air, and the legs and feet were always immersed. The trunk cylinder was exposed to both air and water of varying depth and the clothing insulation covering the trunk was in transition. Thus, the environmental and clothing parameters for the trunk needed to be modified to take these factors into account. Based on the experimental design, it was assumed that 20% of the torso was exposed to air while 80% was immersed during CH, whereas during WA, 80% of the torso was exposed to air while 20% was immersed. Therefore, the adjusted parameters were calculated using area weighted values for air and water which reflected the immersion depth.

### Simulation and evaluation

CTM simulations were run for 36 individual trials in CH10, CH15, WA10 and WA15. The measured  $T_{re}$  was compared with the predicted  $T_{re}$  using paired  $t$  tests and the root mean square deviation (RMSD). RMSD quantifies the average difference between predicted

**Table 1** Individual physical characteristic of subjects

Subject	Height (m)	Weight (kg)	Body fat (%)	Age	$\text{VO}_2\text{max}$ ( $\text{ml kg}^{-1} \text{min}^{-1}$ )
A	1.78	86.6	14.7	19	48.2
B	1.93	77.3	8.1	25	38.9
C	1.83	70.7	14	20	44.4
D	1.80	72.4	14.7	19	50.4
E	1.73	64.1	12.9	18	47.2
F	1.75	74.5	17	20	42.5
G	1.73	66.3	15	18	47.8
H	1.70	65.4	19	20	47.2
I	1.75	76.1	16.4	18	48.5
J	1.77	80.4	17.7	19	57.1

and observed measurement across time (Haslam and Parsons 1994; Kraning and Gonzalez 1997). The RMSD was calculated between the observed and predicted temperatures using a 10-min time interval. Data were analyzed using a two-factor (trial  $\times$  time) repeated-measures ANOVA to compare between predicted and observed values. Trials are defined as the measured and predicted values. When significant  $F$  ratios were calculated, paired comparisons were made post hoc using a Tukey HSD test. The level of significance for differences reported is  $P < 0.05$ . To further investigate the potential influences of shivering thermogenesis and muscle blood flow in legs on  $T_{\text{c}}$  responses in the LF group, CTM was modified slightly and run under two particular conditions. The modifications included inhibition of shivering or an increase in basal muscle blood flow rate in legs from 1.6 ml/min per 100 ml tissue (Xu and Werner 1997) to 5 ml/min per 100 ml tissue (Johnson 1989). Limbs and extremities have large vasomotor regulation (Toner and McArdle 1996) and thus, blood flow in these areas may be high either before or during exercise in cold water and therefore play a critical role in  $T_{\text{c}}$ .

## Results

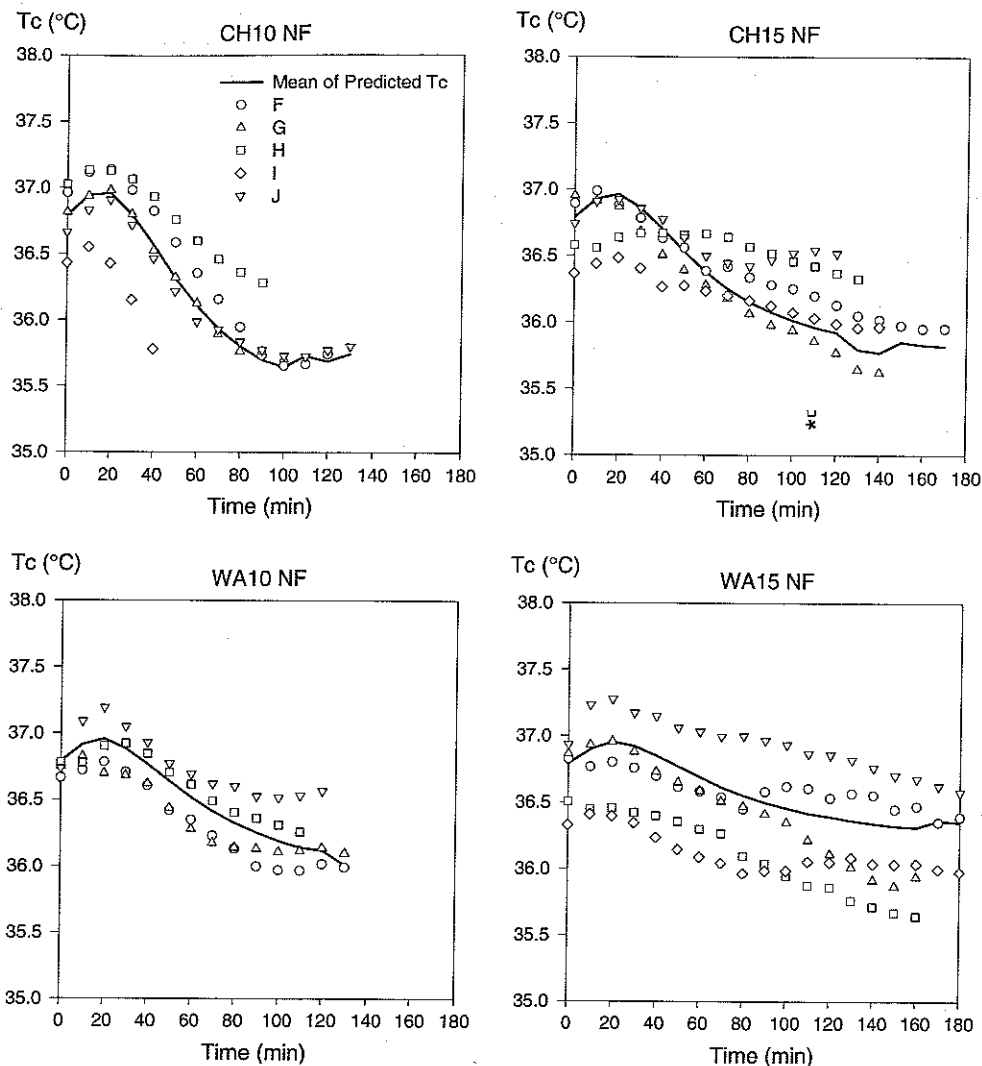
Figure 1 shows the measured  $T_{\text{c}}$  of each individual in NF group and mean of the predicted  $T_{\text{c}}$  at CH10, CH15, WA10 and WA15. The observed  $T_{\text{c}}$  increased slightly during the beginning of immersion due to vasoconstriction, and then started to fall after reaching its peak in about 20 min. The predicted  $T_{\text{c}}$  was close to the measured  $T_{\text{c}}$  and within the span of experimental values. Paired  $t$  tests indicated that differences between the measured and predicted  $T_{\text{c}}$  were not significant ( $P > 0.05$ ) at CH10, CH15 and WA10, but at WA15 there were no significant differences except for the data at 110 min ( $P < 0.0001$  or  $0.0001$ ). Figure 2 shows the measured  $T_{\text{c}}$  of each individual in LF group and mean of the predicted  $T_{\text{c}}$  for each of the trials.  $T_{\text{c}}$  responses of the LF group appeared to be different from the NF group. At the beginning of immersion, the  $T_{\text{c}}$  of LF group increased for a shorter period, and then started to drop quickly. For one subject,  $T_{\text{c}}$  dropped immediately after immersion. Paired  $t$  tests indicated that the differences between measured  $T_{\text{c}}$  and predicted  $T_{\text{c}}$  were significant ( $P < 0.0001$ ) at all four conditions. Figure 2 also shows the mean of the adjusted predicted  $T_{\text{c}}$ , i.e. the prediction with an increased muscle blood flow in legs; the adjusted prediction results match more closely with observed values than the original prediction.

Table 2 shows the mean (SD) of the measured and predicted  $T_{\text{c}}$  at the end of each trial, the RMSD and the average (SD) immersion time for each trial. The predicted  $T_{\text{c}}$  for the NF group was within the range of the measured  $T_{\text{c}} \pm \text{SD}$  in all four trials, with RMSD values ranging from 0.15 to 0.32°C. These RMSD values were within or close to the SD values of NF. For the LF group, the predicted  $T_{\text{c}}$  was within the range of the measured  $T_{\text{c}} \pm \text{SD}$  only at CH15 and was higher than the measured  $T_{\text{c}}$  for the other three trials with the RMSD values ranging from 0.3 to 0.6°C. When the muscle blood flow was adjusted for LF group, the predicted  $T_{\text{c}}$  at the end of immersion were 35.43°C for CH10, 35.13°C for CH15, 35.67°C for WA10 and 35.65°C for W15 separately and their correspondent RMSD were 0.28, 0.26, 0.24 and 0.26°C, respectively. The adjusted predicted  $T_{\text{c}}$  was closer to observed  $T_{\text{c}}$  and RMSD were smaller in comparison with the original RMSD. The immersion time for the NF group was about 75–123% longer than the LF group.

The effects of shivering intensity on  $T_{\text{c}}$  responses are shown in Fig. 3, the results for Subject C at CH10 and Subject E at WA10 are depicted as an example. When shivering was inhibited in the CTM simulation, the predicted  $T_{\text{c}}$  was lower than the original simulation when shivering was not inhibited. Thus, the predicted  $T_{\text{c}}$  was closer to the measured  $T_{\text{c}}$  for both subjects at CH10 or WA10 conditions and the RMSD was reduced from 0.38 to 0.24°C for Subject C and from 0.59 to 0.47°C for Subject E when shivering was inhibited in the simulation. When the muscle blood flow in legs was increased to 5.0 ml/min per 100 ml tissue, the predicted  $T_{\text{c}}$  was improved significantly and matched the measured  $T_{\text{c}}$  well. After adjusting for muscle blood flow, the RMSDs were 0.14°C for Subject C at CH10 and 0.15 for Subject E at WA10.

## Discussion

The CTM was successfully used to simulate individual thermal responses to cold exposure. Only a few models consider individual characteristics and all were designed for hot or warm/cool environments. Havenith (2001) developed an individualized model of human thermoregulation for simulation of heat stress responses while Zhang and her colleagues (2001) developed a body builder model and incorporated this into the UC Berkeley thermal comfort model to predict variances in thermal response between individuals. The CTM was designed for the cold with the capability for individualization and provides a significant upgrade to the original model and could be utilized for many



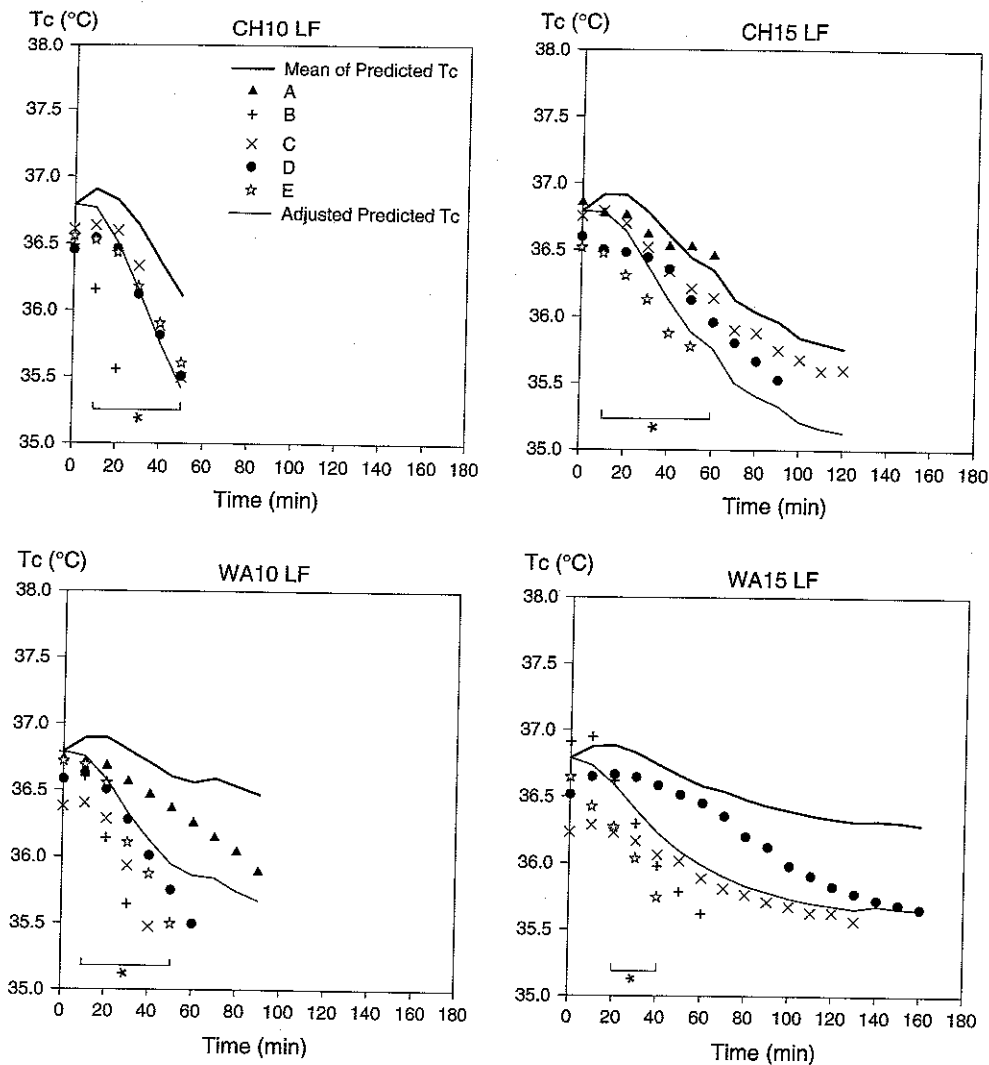
**Fig. 1** Time versus individual measured core temperatures (each symbol represents one individual) and mean of predicted core temperature (line) in subjects with a % fat of 15–19% (NF). Trials consisted of walking at  $0.44 \text{ m s}^{-1}$  at chest  $10^\circ\text{C}$  (CH10), Chest

$15^\circ\text{C}$  (CH15), Waist  $10^\circ\text{C}$  (WA10) and Waist  $15^\circ\text{C}$  (WA15). Asterisk denotes predicted value is significantly different than the mean measured value at specified time points

applications. Significant inter-individual variance in rectal temperature, skin temperature and energy expenditure in response to mild cold has been reported (Marken Lichtenbelt et al. 2002) and data from the current study clearly demonstrate inter-individual differences during light exercise in cold water (e.g., one LF subject reached  $T_{\text{c}}$  of  $35.5^\circ\text{C}$  in about 20 min at CH10 conditions while two NF subjects maintained their  $T_{\text{c}}$  above  $35.5^\circ\text{C}$  after 120 min). This study found that, in these ten subjects during immersion in cold water at two depths, CTM predicted  $T_{\text{c}}$  responses with acceptable accuracy for certain individuals, mostly NF people, and tended to overpredict  $T_{\text{c}}$  responses for other individuals, mostly LF people.

CTM requires height, weight, percentage of body fat, age, and maximal oxygen consumption to predict

individual thermal responses. Height, weight and percentage of body fat determine the geometrical sizes of each cylinder and layer (Xu 1996). Body fat, age and maximal oxygen consumption are used to determine the shivering intensity, maximal shivering capacity and shivering fatigue (Xu et al. 2005). In a previous study (Xu et al. 2005), CTM predictions were in good agreement with measured observations for ten male and female subjects immersed in  $8\text{--}10^\circ\text{C}$  water who had body fat percentages ranging from 14.9 to 33.6%. The current study further demonstrated that CTM prediction for the NF group was in good agreement with observation during partial immersion at two depths during slow walking. The five inputs appear to adequately describe individual responses to cold-stress for a certain group of individuals, i.e. people with a normal



**Fig. 2** Time versus individual measured core temperatures (each symbol represents one individual), mean of predicted core temperature (line) in subjects with a % fat of  $\leq 14.7\%$  (LF) and mean of predicted core temperature with increased muscle blood flow in legs (adjusted predicted core temperature, thin line). Trials

consisted of walking at  $0.44 \text{ m s}^{-1}$  at chest  $10^\circ\text{C}$  (CH10), chest  $15^\circ\text{C}$  (CH15), waist  $10^\circ\text{C}$  (WA10) and waist  $15^\circ\text{C}$  (WA15). Asterisk denotes predicted value is significantly different than the mean measured value at specified time points

percentage of body fat. What other physiological information, inputs or anthropometric data (e.g. length of the leg) would be required to describe individual responses to cold, especially in individuals with a low percentage of body fat?

There are initial differences before cold exposure between the measured and predicted  $T_c$ . Predicted  $T_c$  was fixed at a constant value of  $36.8^\circ\text{C}$  in the current CTM construct, while the measured pre-exposure  $T_c$  varied between and within subjects. As shown in Fig. 2, the initial temperatures of the LF group ranged from  $36.2$  to  $36.9^\circ\text{C}$  in trial W15. Subject C (symbol  $\times$ ) had an initial temperature of  $36.2^\circ\text{C}$  in W15 and  $36.7^\circ\text{C}$  in CH15. As the endurance times for the LF group were short due to rapid core cooling, initial  $T_c$  increased in

relative importance. With a given cooling rate, a lower initial  $T_c$  caused subjects to reach the experimental end-point in a shorter time. Figure 2 shows that the measured  $T_c$  for most subjects was lower than the predicted  $T_c$ . Individuals with low initial core temperatures and low percent body fat appear more vulnerable to hypothermia. It might improve prediction accuracy if CTM was modified to allow the input of an individual's initial  $T_c$ .

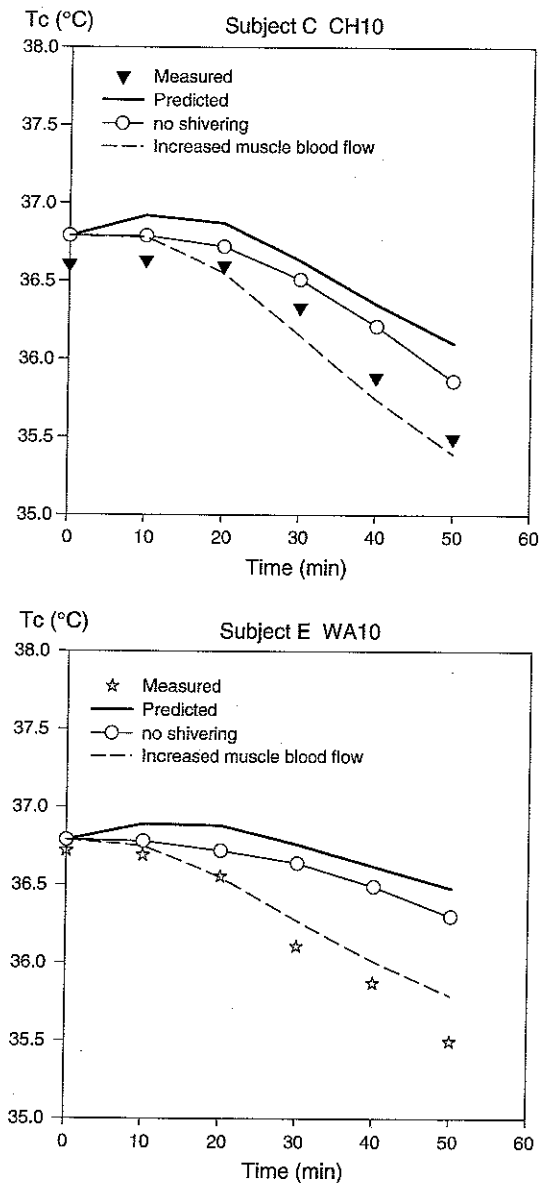
CTM considered two basic roles of body fat in maintaining body heat balance and core temperature during cold exposure: insulation and attenuation of shivering heat production. Fat provides insulation, due to the low heat conductivity, reported to be  $\sim 0.15\text{--}0.5 \text{ W/m}^\circ\text{C}$  (Werner and Buse 1988), thus providing higher

**Table 2** Mean (SD) measured and predicted core temperature ( $T_c$ ) at the end of each trial, root mean square deviation (RMSD), and mean (SD) immersion time during each trial for the normal fat (NF) and low fat (LF) groups

Trials	$T_c$ (°C) measured predicted	RMSD (°C)	Time (min)
NF			
CH10	35.85 (0.22) 35.72	0.32	96 (35)
CH15	36.08 (0.35) 35.85	0.23	140 (19)
WA10	36.23 (0.25) 35.98	0.15	123 (10)
WA15	36.04 (0.29) 36.26	0.30	172 (12)
LF			
CH10	35.54 (0.05) 36.13	0.52 <sup>a</sup>	43 (19)
CH15	35.87 (0.37) 36.14	0.31 <sup>a</sup>	80 (32)
WA10	35.60 (0.18) 36.56	0.60 <sup>a</sup>	54 (23)
WA15	35.65 (0.07) 36.46	0.58 <sup>a</sup>	98 (57)

<sup>a</sup> RMSD with adjusted prediction are 0.28, 0.26, 0.25, and 0.26°C, respectively

thermal resistances than either skin or muscle tissue (Toner and McArdle 1988). The mean thickness of subcutaneous fat in male subjects with 8.8 to 27.2% percent body fat ranged from 1.1 mm to 9.6 mm (Veicsteinas et al. 1982). That, with a given temperature difference over the fat layer and a constant heat conductivity, would represent about an 8.7-fold difference in heat flow, i.e. heat flow with 8.8% body fat is about 8.7 times as large as the heat flow with 27.2% body fat. Based on the current CTM construct, the fat thickness is ~3.7 mm for 10% body fat and 9.6 mm for 25% in a human with height of 1.83 m and weight of 70.7 kg. Many studies have clearly demonstrated the benefits of body fat in maintenance of core temperature during cold-water immersion. A relatively fat person with large subcutaneous fat and minimal perfusion of the skin and extremities can withstand the challenges of cold water more effectively than a leaner counterpart (Toner and McArdle 1996; Stocks et al. 2004). The role of fat as insulation becomes even more important during exercise, as the insulation provided by muscle, which provides 60–75% of body insulation, is decreased (Veicsteinas et al. 1982; Park et al. 1984). However, if shivering can increase heat production substantially, the insulation provided by fat may be less important. During 90 min immersion in 18, 22 and 26°C water, low fat male subjects were able to maintain a similar  $T_c$  when compared to their high fat counterparts due to greater shivering thermogenesis (Glickman-Weiss et al. 1991). In addition, shivering metabolism is inversely proportional to the percentage of body fat during cold-water immersion (Tikuisis et al. 1988). According to the CTM construct, low fat individuals have a thin fat layer and a high metabolic rate. Yet the high-predicted metabolic rate does not appear



**Fig. 3** Measured and predicted core temperatures for subject C at chest 10°C (CH10) immersion (*top*) and for subject E at waist 10°C (WA10) immersion (*bottom*), predicted core temperatures while shivering was inhibited or leg muscle blood flow was increased to 5.0 ml/min per 100 ml tissue in the CTM simulation

to be the reason that the predicted  $T_c$  is higher than the measured  $T_c$ . As shown by the two individual examples in Fig. 3, even when shivering heat production is inhibited (i.e. set to zero) in CTM, the predicted  $T_c$  is still higher than the measured  $T_c$  for both subject C in the CH10 trial and subject E in the WA10 trial. Therefore, the insulation function of body fat and shivering heat production appear not to explain the phenomena, suggesting other mechanisms may contribute to the rapid decline in  $T_c$  observed in the LF group.

Blood flow influences thermal responses to cold but its effects have not been fully characterized yet, as the

measurement of blood flow, especially muscle blood flow, is difficult. During cold water immersion, the high gradient between the core and muscle in the extremities [e.g. 18°C during 8°C water immersion (Bristow et al. 1994)] and high amount of muscle mass, i.e. ~40% of body mass could facilitate heat exchange between the core and extremity even with relatively low blood flows in muscle. The limbs and extremities, body areas that have large vasomotor regulation, have two adjustable thermal resistances: muscle blood flow and skin blood flow (Toner and McArdle 1996). At the beginning of cold immersion,  $T_c$  increased slightly for ~10 min with LF group and ~20 min with NF group due to vasoconstriction and then started to decrease. As shown in Fig. 2, when the leg muscle blood flow (i.e. blood flow before cold exposure) is increased to 5 ml/min per 100 ml tissue (from 1.6 ml/min per 100 ml tissue), the predicted  $T_c$  for LF agreed with the measured  $T_c$  more closely in all four trials. Figure 3 indicated that  $T_c$  is more sensitive to changes in leg muscle blood flow than to the changes in shivering. Hence, the CTM simulations support an interpretation that high leg muscle blood flow causes a rapid decline in  $T_c$ . A recent study demonstrated that individual variance in muscle blood flow is greater than individual variance in skin blood flow (Kenny et al. 2006). Thus it is reasonable to postulate that individual differences in muscle blood flow partly causes the individual thermal responses to partial immersion. Furthermore, body fat could modulate the effects of muscle blood flow on  $T_c$  response. First, a low percent body fat is associated with a thin fat layer and the muscle is close to the skin surface, which could cause the outer layer of muscle in legs to cool down quickly at the beginning of immersion, as well as cool down the temperature of venous blood, leading to core cooling. This seems consistent with a previous observation that older swimmers and boys of given trunk fat thickness generally had less limb fat and cooled faster than younger swimmers and girls (Sloan and Keatinge 1973). Second, body fat composition may also affect blood flow rates and vasomotor regulations. Lean individuals (ectomorphs) have a higher blood volume per unit weight than fat individuals (endomorphs) (Gregersen and Nickerson 1950). Blood flow in muscle is more severely restricted in fat subjects than in thin subjects in water of critical temperature (Park et al. 1984). This might partly explain the differences in thermal responses of the NF and LF groups to cold immersion.

CTM simulated effects of the muscle blood flow in legs on  $T_c$  cooling and the prediction indicated that leg muscle blood flow in legs is a possible contributor to the rapid decline in  $T_c$  for LF people. In the experiments, the subjects were walking at a speed of 0.44 m/s

on a treadmill during immersion and exercise increases muscle blood flow rates in legs. Other reports indicate blood flow in the calf during rest of ~3.6 ml/min 100 ml tissue (Savard et al. 1985) and blood flow to inactive muscle of ~5–10 ml/min per 100 g muscle (Johnson 1989). Thus the revised muscle blood flow rates in the CTM simulation, 5.0 l/min per 100 ml tissue, seem physiologically reasonable and the adjusted predicted  $T_c$  consistent with observations. Exercise substantially lowers body insulation during cold immersion, probably by increasing muscle blood flow (Sloan and Keatinge 1973; Yeon et al. 1987). The contribution from cooled limb blood flow to a decrease in  $T_c$  has also been observed during cold-water immersion where blood flow to the limbs was occluded (Mittleman and Mekjavic 1988). Even under neutral environmental conditions, convective heat transfer through blood flow likely contributes to core temperature changes and heat redistribution between the muscle and core region during the postexercise period (Kenny et al. 2006). Due to the possible contribution of leg muscle blood flow to the observed  $T_c$  responses, individuals with low body fat percentages are potentially at greater risk during exercise while only partially immersed.

One limitation of the present study was the separation of the groups for analysis. The LF group had only one very low fat subject (i.e. 8.1%) and the NF group had one high fat subject (i.e. 19%), but the fat differences between the two groups were not large. Therefore, further study is needed to examine whether the relation between CTM accuracy and fat % observed in this study could be expanded to a broader scope. However, findings of this study do suggest that biophysical and physiological parameters (i.e. height, weight, and body fat % and shivering heat production) do not fully explain large individual differences in  $T_c$  responses to partial immersion. Muscle blood flow, either basal values or increases due to exercise, and blood flow redistribution could play critical roles in thermal equilibrium and account for individual differences in  $T_c$  responses during immersion. Two prior studies demonstrate the need for an independent compartment, i.e. muscle, in addition to core and shell, to assess the heat balance status of the body (Tikuisis 2003; Jay et al. 2006). Convection through blood flow would be an effective way to exchange heat among these three compartments. Although thermal responses to cold have been well studied, there is limited quantitative information and knowledge about how cold impacts regional blood flows. Modeling techniques have been long used to investigate the effects of blood flow on local tissue temperature distribution during induced regional hyperthermia therapies (Brinck and Werner 1995;

Kolios et al. 1998; Alekssev et al. 2005). CTM simulation demonstrated the potential contribution of muscle blood flow to  $T_{\text{c}}$  cooling by means of a whole body thermoregulatory model.

Immersion at various depths represents a relatively complex set of environmental conditions. Heat loss in air is significantly different from heat losses in water. Clothing absorbs water through capillary action and becomes progressively wetter, thus the thermal insulation values change over time. According to the basic CTM construct, each cylinder should be exposed to a uniform environment with a specific set of physical and clothing parameters. To adapt the model for partial immersion, adjustments based on the percentage of the cylinder that was immersed were made to the inputs for the torso section. If the percentage was changed by  $\pm 5.0\%$  from the 80.0% during CH, the deviations of CTM prediction at end of 180 min immersion were less than  $0.1^{\circ}\text{C}$ . The CTM predictions neglected the influence of exercise for simplicity, as the exercise load (i.e. walking at 0.44 m/s) was low. In addition, for modeling the trials, measured heat transfer coefficients during immersion were used, instead of model default values, to make the simulation more realistic and account for the effect of water movement on convective heat loss. Results from this study indicate that adjustments (i.e. parameters for the torso section) to the model based on best available information are necessary to ensure that the inputs and predictions accurately represent the actual conditions, especially when CTM is used to predict thermal responses in the field. To ensure that the inputs are realistic, rigorous evaluation to identify all possible scenarios is required. When the information available is limited, it might be necessary to run thermal response simulations for the worst and best cases. The results, which indicate that the basic CTM can be successfully adapted to the more complex scenario of partial immersion, suggest that CTM could be applied to other partial immersion scenarios such as one foot or one leg immersion.

## Conclusions

CTM predicted, in this study with acceptable accuracy, core temperature responses to immersion at various depths for certain individuals, i.e. those with normal body fat compositions. The differences in the measured and predicted core temperatures for people with low body fat composition are likely due to initial temperature (pre-exposure temperature) and muscle blood flow in the legs. Simulation analysis suggested that the leg muscle blood flow may contribute significantly to

the rapid drop in core temperature and partly account for individual thermal responses to partial immersion. CTM can be adapted to non-uniform environments by adjusting the input accordingly. When scenarios are complex and/or available information is minimal, it would be necessary to run CTM for the worst and best cases, and the influential factors, e.g. initial temperature and leg muscle blood flow, should be considered.

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